

**LOW POWER DIFFERENTIAL AMPLIFIER
POWERED BY MULTIPLE UNEQUAL POWER SUPPLY VOLTAGES**

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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to differential amplifiers, and in particular, to differential amplifiers operating in a low power circuit environment.

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2. Description of the Related Art

Referring to Figures 1A and 1B, switched capacitor circuits are well known in the art. Such circuits can be used to provide various signal filtering or integration functions and typically have two phases, or states, of operation: a sample phase 10a and a holding phase 10b. As is well known in the art, switches (not shown) driven by nonoverlapping clock signal phases (not shown) cause input and feedback capacitances C coupled to the input terminals 11a, 11b of the differential amplifier 12, to switch between reception of the positive Vinp and negative Vinn phases of the differential input signal Vin, and circuit ground GND, thereby feeding back the positive Voutp 13a and negative Voutn 13b signal phases of the output signal Vout. Load capacitances Cload couple the output signal terminals 13a, 13b, to circuit ground GND.

As is further well known, modern complementary metal oxide semiconductor (CMOS) processes are continuing to scale down in terms of power supply voltage magnitudes. Indeed, some circuits are now expected to operate at power supply voltages at or below one volt. Particularly for the amplifier 12 in a switched capacitor circuit, such low power supply voltages result in lost headroom for the analog amplifier circuitry.

Referring to Figure 2, a typical implementation of the differential amplifier 12 includes two circuit branches 12a, 12b formed by the serial connections of transistors M2 and M4 and transistors M1 and M3, powered by a power supply voltage VDD and driven by a tail current source 14, which together produce a total amplifier bias current of $2 * Islew$. When used in the switched capacitor circuit 10, the overall circuitry has one pole at a dominant pole position, and a feedback factor f associated with the switched capacitors C. (It should be understood that this simplified analysis ignores the input capacitance of the differential amplifier circuit 12.)

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At low power supply VDD voltages, it is difficult to maintain the transistors M1,

M2, M3, M4 of the amplifier 12 in their respective operational states of saturation. This difficulty increases significantly when cascode devices are added to the P-MOS and N-MOS portions of the circuit 12. Accordingly, high DC gain cannot be achieved.

Moreover, simply increasing the power supply voltage VDD to improve headroom will significantly increase power dissipation of the circuit 12.

Referring to Figure 3, the aforementioned dominant pole causes the open loop gain bandwidth product GBW' for the amplifier 12 to be a function of the transconductance gm of the input transistors M1, M2 and the switched C and load Cload capacitances. The feedback factor f, which is equal to 0.5 for equal valued switched capacitances C, affects the closed loop gain bandwidth product GBW accordingly ($GBW=GBW'*f$).

SUMMARY OF THE INVENTION

In accordance with the presently claimed invention, a low power differential amplifier is powered by a plurality of unequal power supply voltages. The input stage operates at a higher power supply voltage so as to maintain its transistors in operational states of saturation while providing a sufficient dynamic signal voltage range. The output stage operates at a lower power supply voltage while providing a sufficient dynamic signal current range.

In accordance with one embodiment of the presently claimed invention, a low power differential amplifier powered by a plurality of unequal power supply voltages includes power supply terminals, telescopic differential amplifier circuitry and voltage follower circuitry. A first power supply terminal conveys a first power supply voltage having a first voltage magnitude. A second power supply terminal conveys a second power supply voltage having a second voltage magnitude which is less than the first voltage magnitude. The telescopic differential amplifier circuitry, coupled to the first power supply terminal, responds to reception of the first power supply voltage and an input differential signal by providing an intermediate differential signal corresponding to the input differential signal. The voltage follower circuitry, coupled to the second power supply terminal and the telescopic differential amplifier circuitry, responds to reception of the second power supply voltage and the intermediate differential signal by providing an output differential signal corresponding to the intermediate differential signal.

In accordance with another embodiment of the presently claimed invention, a low power differential amplifier powered by a plurality of unequal power supply voltages

includes power means, differential amplifier means and voltage follower means. A first power means is for conveying a first power supply voltage having a first voltage magnitude. A second power means is for conveying a second power supply voltage having a second voltage magnitude which is less than the first voltage magnitude. The 5 differential amplifier means is for receiving the first power supply voltage and an input differential signal and responding thereto by generating an intermediate differential signal corresponding to the input differential signal. The voltage follower means is for receiving the second power supply voltage and the intermediate differential signal and responding thereto by generating an output differential signal corresponding to the intermediate 10 differential signal.

In accordance with still another embodiment of the presently claimed invention, a low power differential amplifier powered by a plurality of unequal power supply voltages includes power supply terminals and amplifier circuitries. A first power supply terminal conveys a first power supply voltage having a first voltage magnitude and a first power supply current having a first current magnitude. A second power supply terminal conveys a second power supply voltage having a second voltage magnitude and a second power supply current having a second current magnitude, wherein the first voltage magnitude is greater than the second voltage magnitude and the first current magnitude is less than the second current magnitude. First amplifier circuitry, coupled to the first power supply 15 terminal, responds to reception of the first power supply voltage, the first power supply current and an input differential signal by providing an intermediate differential signal corresponding to the input differential signal. Second amplifier circuitry, coupled to the second power supply terminal and the first amplifier circuitry, responds to reception of the second power supply voltage, the second power supply current and the intermediate 20 differential signal by providing an output differential signal corresponding to the intermediate differential signal.

In accordance with yet another embodiment of the presently claimed invention, a low power differential amplifier powered by a plurality of unequal power supply voltages includes power means and amplifier means. A first power means is for conveying a first power supply voltage having a first voltage magnitude and a first power supply current having a first current magnitude. A second power means is for conveying a second power supply voltage having a second voltage magnitude and a second power supply current having a second current magnitude, wherein the first voltage magnitude is greater than the second voltage magnitude and the first current magnitude is less than the second current 25 magnitude. A third power means is for conveying a third power supply voltage having a third voltage magnitude and a third power supply current having a third current magnitude, wherein the second voltage magnitude is greater than the third voltage magnitude and the second current magnitude is less than the third current magnitude. The amplifier means is for receiving the first power supply voltage, the first power supply current, the second power supply voltage, the second power supply current, the third power supply voltage, the third power supply current and an input differential signal by providing an intermediate differential signal corresponding to the input differential signal. The 30 amplifier means is for receiving the intermediate differential signal and responding thereto by generating an output differential signal corresponding to the intermediate differential signal.

magnitude. A first amplifier means is for receiving the first power supply voltage, the first power supply current and an input differential signal and responding thereto by generating an intermediate differential signal corresponding to the input differential signal. A second amplifier means is for receiving the second power supply voltage, the second power supply current and the intermediate differential signal and responding thereto by generating an output differential signal corresponding to the intermediate differential signal.

BRIEF DESCRIPTION OF THE DRAWINGS

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Figure 1A and 1B are circuit schematic diagrams of the sample and hold phases of a conventional switched capacitor circuit.

Figure 2 is a schematic diagram of a conventional differential amplifier circuit.

15 Figure 3 is a graph depicting the gain versus frequency characteristic of the circuit of Figure 2 when used in the circuit of Figures 1A and 1B.

Figure 4 is a schematic diagram of a differential amplifier circuit in accordance with one embodiment of the presently claimed invention.

Figure 5 is a graph of the gain versus frequency characteristic of the circuit of Figure 4 when used in the circuit of Figures 1A and 1B.

20 Figure 6 is a schematic diagram of a differential amplifier circuit in accordance with another embodiment of the presently claimed invention.

Figure 7 is a schematic diagram of a differential amplifier circuit in accordance with still another embodiment of the presently claimed invention.

25 Figure 8 is a schematic diagram of a differential amplifier circuit in accordance with yet another embodiment of the presently claimed invention.

DETAILED DESCRIPTION

The following detailed description is of example embodiments of the presently 30 claimed invention with references to the accompanying drawings. Such description is intended to be illustrative and not limiting with respect to the scope of the present invention. Such embodiments are described in sufficient detail to enable one of ordinary skill in the art to practice the subject invention, and it will be understood that other

embodiments may be practiced with some variations without departing from the spirit or scope of the subject invention.

Throughout the present disclosure, absent a clear indication to the contrary from the context, it will be understood that individual circuit elements as described may be singular or plural in number. For example, the terms "circuit" and "circuitry" may include either a single component or a plurality of components, which are either active and/or passive and are connected or otherwise coupled together to provide the described function. Additionally, the term "signal" may refer to one or more currents, one or more voltages, or a data signal. Within the drawings, like or related elements will have like or related alpha, numeric or alphanumeric designators.

Further, while the following discussion is in a context of certain arrangements of N-type and P-type metal oxide semiconductor field effect transistors (e.g., N-MOSFETs M1, M2, M5 and M6, and P-MOSFETs M3, M4, M7, M8, M9 and M10, respectively) powered by a positive power supply voltage VDD (where VSS is a negative voltage or ground GND potential), it will be readily understood by one of ordinary skill in the art that corresponding circuit arrangements can be implemented in accordance with well known circuit design techniques in which the N-MOSFETs are replaced with P-MOSFETs, the P-MOSFETs are replaced with N-MOSFETs, and powered is provided by a negative power supply voltage VSS (where VDD is a positive voltage or ground GND potential).

Referring to Figure 4, a differential amplifier 112 in accordance with one embodiment of the presently claimed invention is powered by multiple unequal power supply voltages. The input stage 116 includes two circuit branches 116a, 116b formed by the serial connections of transistors M2 and M4 and transistors M1 and M3, powered by the higher of the two power supply voltages VDD HI, and driven by a tail current source 120 sinking the lower of the two bias currents Ibias (discussed in more detail below). In accordance with well known circuit principles, transistors M3 and M4 serve as load devices for the input transistors M1, M2, and are biased in on states by a bias voltage Vbias.

The output stage 118 includes two output circuit branches 118a, 118b formed by the serial connections of transistor M5 and current source 122a and transistor M6 and current source 122b. Each of these circuit branches 118a, 118b is powered by the lower of the two power supply voltages VDD LO and conducts the higher of the two power supply currents Islew which is sunk by the current sources 122a, 122b. Compensation capacitances Cc coupled between the gate and drain terminals of the output transistors

M5, M6 establish the open loop gain bandwidth product GBW' for the circuit 112.

Referring to Figure 5, the differential amplifier 112 of Figure 4, when used in the switched capacitor circuit of Figures 1A and 1B, can be designed to maintain the same open loop gain bandwidth product GBW' as the circuit 12 of Figure 2, which is a function 5 of the load C_{load} and switched C capacitances and feedback factor f. The output stage 118 serves as a level shifting stage by nature of the voltage follower action of output transistors M5 and M6. This output stage 118 does not significantly load the input stage 116 because the gate-to-source capacitance C_{gs} of the output transistors M5, M6 is bootstrapped by the source follower operation of these transistors M5, M6. Accordingly, 10 the output, or load, capacitance for the input stage 116 is small, and is primarily that of the overlap capacitance of the output transistors M5, M6 (i.e., the capacitance formed by the inherent overlap of the gate terminal and the drain and source regions of the transistor) plus the three gate-to-drain capacitances C_{gd} of the transistors at the output terminals 117a, 117b of the input stage 116 (i.e., transistors M1, M3 and M5 at terminal 117a, and 15 transistors M2, M4 and M6 at terminal 117b). As a result, the input stage 116 can be biased with a very low bias current I_{bias} for the desired gain bandwidth product, thereby significantly reducing the power required from the power supply VDD HI. For example, since the input stage 116 can run on such a very low current, the higher power supply voltage VDD HI can be sourced by a power supply typically used for the input and output 20 circuit functions of the host integrated circuit, or alternatively, it can be generated by any of a number of well known voltage generating techniques such as those used in charge pumps.

As is well known, a switched capacitor system, such as that depicted in Figures 1A and 1B, requires a minimum output current equal to the slew rate requirements.

Accordingly, this current requirement determines the value of the output currents I_{slew} driving the output transistors M5, M6. Hence, for the conventional single stage amplifier 12 (Figure 2) the bias current was twice this amount, i.e., $2^* I_{slew}$. However, in the two-stage design 112 of Figure 4, each circuit branch 118a, 118b of the output stage is biased with such a current I_{slew} . Since these circuit branches 118a, 118b are powered from the lower power supply voltage, the power dissipated by these circuit branches 118a, 118b is significantly lower than the power dissipated by the single stage amplifier 12.

Accordingly, with a sufficient voltage difference between the higher VDD HI and lower VDD LO power supply voltages, the total power dissipated in the two stage amplifier 112 can be significantly below that of the single stage amplifier 12.

Referring to Figure 5, when the amplifier circuit 112 of Figure 4 is used in a switched capacitor system, such as that shown in Figures 1A and 1B, a pole is created in the open loop transfer function of the two-stage amplifier circuit 112 at the same frequency as for the single stage amplifier 12 (Figure 2) before modification by the 5 feedback factor f. The frequency of this pole is a function of the transconductance gm of the output transistors M5, M6 and the load Cload and switched C capacitances of the switched capacitor network (Figures 1A and 1B).

As represented below, the phase margin pm can be calculated as 90 degrees minus the arctangent of frequency ω divided by the frequency ω_p of the pole. When the 10 feedback factor f is applied, the gain bandwidth product GBW is affected, but the frequency ω_p of the pole is not. Therefore, if the frequencies of the pole ω_p and open loop gain bandwidth product GBW' are equal, then the quotient ω/ω_p is simply equal to the feedback factor f. In the ideal case, when the feedback factor equals 0.5, the phase margin pm equals 63 degrees and the signal peaking is -0.4 decibels.

$$\begin{aligned}
 15 \quad \text{Phase Margin} &= 90 - \arctan(\omega/\omega_p) \\
 \text{GBW}' &= \omega_p \\
 \text{Phase Margin} &= 90 - \arctan(f) \\
 &= 90 - \arctan(C/(2C)) \\
 &= 90 - \arctan(1/(2f)) \\
 20 \quad &= 90 - \arctan(0.5) \\
 &= 63 \text{ degrees} \\
 \text{Peaking} &= 20 * \log_{10}(1/[sqrt((1+\cos(pm-180))^2 + (\sin(pm-180))^2)]) \\
 &= -0.4 \text{ dB}
 \end{aligned}$$

With peaking virtually zero, settling behavior is optimized and bandwidth is maximized. In practice, however, the feedback factor f is generally larger, thereby further improving the phase margin pm. Further, since the output transistors M5, M6 are not critical in determining signal offsets or system noise, they can be biased more aggressively than the input transistors M1, M2, thereby increasing their respective transconductances gm. This further increases the frequency of the pole, thereby further improving the phase 30 margin pm.

Referring to Figure 6, a differential amplifier circuit 212 in accordance with another embodiment of the presently claimed invention improves upon the circuit 112 of Figure 4 by adding cascode transistors M7, M8, M9, M10 to increase the signal gain of the first stage 216. In a conventional switched capacitor system, such as that shown in

Figures 1A and 1B, a feedback loop will be provided for the amplifier 12 such that the tail current source 14 (Figure 2) is provided a control voltage (not shown) such that the common mode voltage appearing at the output terminals 13a, 13b is maintained at a desired value. However, with the two-stage amplifier design of the presently claimed invention, no such feedback loop or control is necessary.

It will be recognized that the common mode output voltage at the output terminals 217a, 217b of the input stage 216 will be equal to the common mode output voltage at the output terminals 13a, 13b of the output stage 118 plus one gate-to-source voltage V_{GS} of the output transistors M5, M6. Depending upon the magnitude of the power supply voltage VDD HI powering the input stage 216, this common mode output voltage of the input stage 216 may be too high or too low as compared to the desired headroom for the transistors forming the input stage 216.

Referring to Figure 7, a differential amplifier circuit 312 in accordance with still another embodiment of the presently claimed invention includes additional bias circuitry 314 to modify, e.g., equalize, the common mode output voltages at the output terminals 217a, 217b of the input stage 216 and the output terminals 13a, 13b of the output stage 118. This bias circuitry 314 includes two circuit branches 314a, 314b, each of which can include a resistor R connected in series between the input 216 and output 118 stages, plus serially connected current sourcing 316 and sinking 318 circuits between the power supply terminals VDD HI, VSS/GND, substantially as shown. Depending upon the desired amount of modification or equalization of the common mode output voltages, any one or two or all three additional circuit elements R, 316, 318 may be used to adjust the effective common mode output voltage of the first stage 216. For example, for the effective common mode output voltage of the input stage 216 to appear equal to the common mode output voltage of the output stage 118, the product of the resistance R and the difference current I_{P-IN} will be substantially equal to the gate-to-source voltages V_{GS} of the output transistors M5, M6.

Referring to Figure 8, the differential amplifier circuit 312 of Figure 7 can be controlled using a replica bias circuit 400 in accordance with well known replica biasing techniques. The common mode output voltages at the output terminals 217a, 217b, 13a, 13b of the input 216 and output 118 stages are monitored and used to provide control signals 401ap, 401an, 401bp, 401bn for the current sources 316a, 318a, 316b, 318b of the compensation circuit 314 so as to establish the desired difference current I_{P-IN} such that the first stage 216 maintains the desired effective common mode output voltage.

While the use of this additional biasing circuitry 314 may degrade the output impedance of the first stage 216, since capacitively loaded source follower circuits generally exhibit an effectively negative input resistance at their gate terminals, with proper adjustment, the addition of a small resistance R between the input 216 and output 118 stages can improve the transient signal response overall. An upper limit of the value of the resistance R will be determined by the tolerable amount of phase response degradation caused by an additional transfer function pole that becomes more active as the product R*C_c of the resistance R and compensation capacitance C_c becomes increases.

Various other modifications and alternations in the structure and method of operation of this invention will be apparent to those skilled in the art without departing from the scope and the spirit of the invention. Although the invention has been described in connection with specific preferred embodiments, it should be understood that the invention as claimed should not be unduly limited to such specific embodiments. It is intended that the following claims define the scope of the present invention and that structures and methods within the scope of these claims and their equivalents be covered thereby.